Improvement in the Method for Bias Drift Compensation in Micromechanical Gyroscopes

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Abstract. *In this paper an improvement in method is proposed for the compensation of the bias drift in micromechanical gyroscopes by a change in the sign of the measured quantity. A general model of external factors of influence is proposed that must be taken into account when the method is applied. An information-measurement system is developed and experimental data are taken from two commercial sensors. The derived results are showing considerable improvement in the long-term bias stability when the proposed improvement in method is applied.*

Keywords

Micromechanical gyroscope, bias drift compensation, information-measurement system.

1. Introduction

Micromechanical inertial sensors – accelerometers and gyroscopes - are an indispensable part of modern "strapdown" navigation systems where sensors are fixed in the moving object coordinate system. Gyroscopes measure angular speed and allow mapping local and geographic coordinate systems and double integration of accelerometer data determines position in local frame. The precision of the strapdown systems mainly depends on inertial sensors errors. Basic error sources are [1]:

- change (drift) in bias;
- instability of scale factor;
- noise.

These quantities can be generalized with the following equation [2]:

$$A = \overline{A} + \Delta A_{DC} + v \tag{1}$$

where A is the measured acceleration; $\bar{A}$ is the real acceleration; ΔA_{DC} is the zero offset, and v is white Gaussian noise. The analogous notation is used for a gyroscope where ψ denotes the angular speed.

$$\psi = \overline{\psi} + \Delta\psi_{DC} + v\ . \tag{2}$$

As previously mentioned for deriving real coordinates of a moving object the inertial data must be integrated in time [2]:

$$V = \overline{V} + \Delta A_{DC} t + \int v dt\ , \tag{3}$$

$$P = \overline{P} + \frac{\Delta A_{DC} t^2}{2} + \iint v dt\ , \tag{4}$$

$$\theta = \overline{\theta} + \Delta\psi_{DC} t + \int v dt \tag{5}$$

where V, P and θ denote the speed, the position and the angle, respectively. Obviously the bias drift plays a significant role in the precision of the inertial navigation system. Its changes increase errors in velocity and attitude linearly with time and quadratically in position. This makes a long term inertial-only navigation impossible to be realized without special methods for the decrease or compensation of bias drift.

Different kinds of methods for bias drift compensation are known [3, 4, 5, 6 and 7]. A most frequently applied method [3, 4] is the use of additional external navigation information for the moving object, for example GPS (DGPS). Their main advantage is the absence of cumulative error in time which allows using their data for an adaptive modeling of the current sensor state. Because of the strong dependency of bias drift on temperature, a method of thermostating is proposed in [5]. Thermocompensation with the prior measurement of the temperature dependence law is also used. Other methods applied are the modeling of output characteristics with exponential equations [6] and the application of fuzzy logic systems [7].

The objective of this paper is an improvement of a known method [8] which introduces bias drift compensation with a change in the sign of measured quantity. This change is realized in practice through a mechanical change in the sensor's orientation. The improvement consists of a detailed study and modeling of the external factors that influence the application of the method. It is shown that the sensitivity to linear acceleration is important for the consistency of the method. An equation is derived for the final application of the method with a compensation of the external factors of influence. Real long term measurements with two commercial sensors are provided and the effectiveness of drift compensation is presented.

2. Analysis of the Method

The method of additive components compensation characterized by change in the sign of the measured quantity is a classical one and its application to micromechanical gyroscope is proposed in [8]. The essence is in the mechanical rotation of the sensor's sensitive axis so the quantity of interest changes its sign. In this way all undesirable components in output which do not change their sign between rotations, especially bias drift, are compensated.

In real micromechanical gyroscopes [9, 10] not all of the negative components preserve their sign when a change in the sensor's position occurs. These sensors are typical for their sensitivity to linear acceleration. As represented in Fig. 1, the Earth acceleration must be carefully considered, because its influence obviously does not preserve its sign.

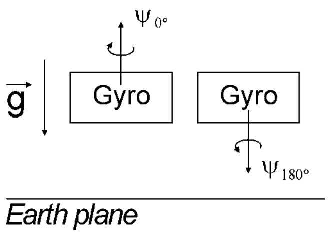

Fig. 1. Bias drift compensation scheme with a change in sign of measured quantity

Taking into account these facts, eqn. (2) is transformed to:

$$\left| \begin{array}{l} \psi_{0^\circ} = \overline{\psi} + \Delta\psi_{DC} + \Delta\psi_g \\ \psi_{180^\circ} = -\overline{\psi} + \Delta\psi_{DC} - \Delta\psi_g \end{array} \right. \tag{6}$$

where ψ_{0°, ψ_{180° are the measured values from a sensor in the corresponding orientations; $\Delta\psi g$ is the influence of the Earth acceleration on the sensor.

To simplify the analysis it is accepted that the sensor's sensitive axis is oriented in parallel to the Earth acceleration vector. Because of the symmetry in the internal structure of micromechanical gyroscopes it is assumed that $\Delta\psi_g$ has the same value but with an opposite sign in positions 0° and 180°. The time needed to change from one position to another is about 1-2 s which is relatively small so it is assumed that the change in the bias is not significant and it is denoted with the same variable $\Delta\psi_{DC}$ in (6).

The subtraction of equations from (6) leads to:

$$(\psi_{0^\circ} - \psi_{180^\circ}) = 2(\overline{\psi} + \Delta\psi_g)\,. \tag{7}$$

In equation (7) the bias effect is removed which is the main purpose of the method, but the sensitivity to linear acceleration participates. In order to calculate $\overline{\psi}$ precisely the value of $\Delta\psi_g$ must be known. Its determination can be realized only when the sensor doesn't observe any angular rotation, i.e. $\overline{\psi} = 0$. Then $\Delta\psi_g$ can be determined from (7):

$$\Delta\psi_g = 0.5(\psi_{0^\circ} - \psi_{180^\circ}),\ \overline{\psi} = 0\,. \tag{8}$$

Generally, achieving $\overline{\psi} = 0$ means that the sensor must be stationary. But in the scheme from Fig. 1, even if stationary, the sensor will be subjected to an angular rotation component arising from the Earth's rotation around its axis. The value of this component depends on the sensor's sensitive axis orientation and the geographic latitude of measurements. According to WGS84 the Earth's rotation speed has a value of ψ_E=4.178074·10^{-3} °/s. The component to the active axis of the sensor (Fig. 1) depends on the latitude according to the equation:

$$\psi_{Earth} = \psi_E.\cos(\varphi_N) \tag{9}$$

where φ_N is the latitude angle. With this additional particularization (8) is transformed to:

$$\Delta\psi_g = 0.5(\psi_{0^\circ} - \psi_{180^\circ}) - \psi_{Earth},\ \overline{\psi} = 0\,. \tag{10}$$

In real navigational systems both quantities $\Delta\psi_g$ and ψ_{Earth} are undesirable. Thus in the method analysis, these components can be combined in one single generalized parameter - ΔN - which must be compensated:

$$\Delta N = (\Delta\psi_g + \psi_{Earth})\,. \tag{11}$$

After the determination of ΔN, it is possible to apply this method when there is a useful signal ($\overline{\psi} = 0$) and its value is calculated from:

$$\overline{\psi} = 0.5(\psi_{0^\circ} - \psi_{180^\circ}) - \Delta N \tag{12}$$

The parameter ΔN consists of two factors. The Earth rotation rate is a relatively small quantity compared to sensitivity data of the majority of sensors and can be neglected. The sensors with stronger sensitivity to linear acceleration will have a larger value for ΔN and an influence to the total method accuracy. Thus it must be defined a priori.

3. Information-Measurement System for Examination of the Method Improvement

A special inertial information-measurement system (IIMS) is developed for a practical research side (Fig. 2). It's based on a microcontroller MSP430F149 [11] and is characterized by a low power consumption, 16-bit RISC architecture and a plenty of hardware modules integrated.

IIMS performs the following functions:

- connection to an external computer system for data processing at a next level;
- external ADC control;
- interface for accelerometers with PWM output;
- two stepper motors control;
- basic processing of measured data (averaging, compensation, calibration).

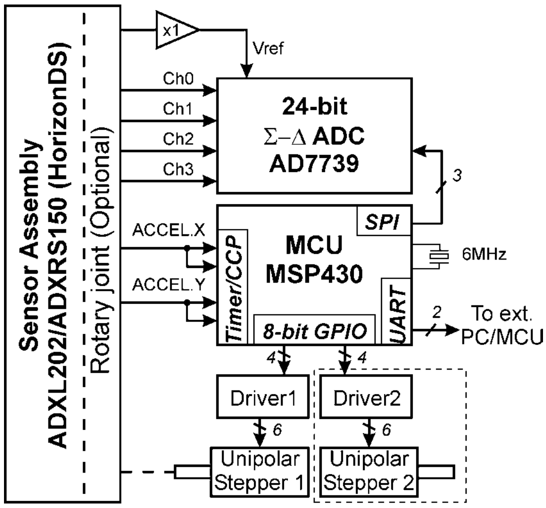

Fig. 2. Block-scheme of IIMS

The integrated serial interface is used for a connection with external systems. A standard PC with the communication speed of 115 200 b/s is used in the implemented measurements.

Although MSP430F149 has its own 12-bit ADC, an external 24-bit Σ-Δ ADC - AD7739 [12] is used for more precise results by decreasing errors from digitization. In Tab. 1 the used AD7739 configuration is shown.

Input configuration	±2,5V, differential mode with chopping
Measurement mode	Single Conversion
Conversion time	2 ms (f_d=500Hz)
Output noise (typ. RMS)	~2μV
Resolution (effective)	21 bits

Tab. 1. AD7739 configuration

To make the precision of the used ADC clearer it is better to convert its typical output noise in °/s. One of sensors investigated, HZ1-90-100A, has scale factor of 22.2 mV/°/s, so the typical noise in AD7739 conversion is $9.01 \cdot 10^{-5}$ °/s. This value is less than the sensor's resolution (Tab. 2) and thus, it may be assumed that AD7739 is precise enough for these measurements.

A stepper motor driver is realized with a general purpose 8bit I/O port, logically separated to 2x4bit, is used for driving up to two unipolar stepper motors. A standard full-step algorithm is implemented.

When a larger number of one-way rotations are needed, a rotary joint is used for the electrical connection between the static and the rotating part.

4. Results

With the IIMS described in the previous section the method is applied to sensor ADXRS150 [9] and HZ1-90-100A [10]. At each position 256 consecutive measurements are done and averaged with a conversion time of 2ms. Including the time needed for the stepper rotation the total time for a single cycle is about 1,79 s. The sensor is stationary – there is no other input signal except for the Earth rotation rate.

Parameter	Value
Range	±90°/sec
Scale factor (±2%)	22.2 mV/°/sec
Threshold and sensitivity	< 0.004°/sec
Sensitivity to linear acceleration	< 0.06°/sec/g
Short term stability (100 s, constant temperature)	< 0.05°/sec

Tab. 2. HZ1-90-100A main specifications

Under these conditions measurements are taken during a week-period and in different parts of the day at room (~20°C) and refrigerator (~4°C) temperature. The duration of data sampling is from 90 to 200 minutes. The averaged values for ΔN are given in Tab. 3.

Measurement No.	ΔN, °/sec (~20°C)	ΔN, °/sec (~4°C)
1	0.00217	0.00713
2	0.00203	0.00337
3	0.00218	0.00366
4	0.00301	0.00376
5	0.00366	0.00361
6	0.00485	0.00244
7	0.00406	0.00107
8	0.00255	0.00738
9	0.00213	0.00291
10	0.00434	0.00360
11	0.00366	0.00380
12	0.00333	0.00353
13	0.00222	0.00330
Average	0.00309	0.00381
Standard deviation	0.000959	0.001697

Tab. 3. Measured value of ΔN at two temperatures for HZ1-90-100A sensor

The same measurements under the same conditions (but only at room temperature instead) are provided with the ADXRS150. Results are shown in Tab. 4.

Fig. 3 to 10 represent graphically two of the measurements for each sensor. The output in each orientation and the compensated value are represented. Compensated value is derived form equation (12) where ΔN is substituted with the average values from tables.

Obviously, in spite of the high noise level in the ADXRS150 output, the compensated bias drift (Fig. 4 and 5) is characterized by a much better long-term stability according to the drift from measurements in positions 0°

and 180°. It must be noted that these small values of the drift for a period of 9000 s are achieved only with proper ΔN determination and removal. Not taking into account ΔN adds a significant offset (the value of ΔN itself) to the finally compensated signal from this method and aggravates its accuracy.

Measurement No.	ΔN, °/sec (~20°C)
1	0.40122
2	0.41402
3	0.39435
4	0.39304
5	0.35952
6	0.37071
7	0.40430
8	0.40498
9	0.40363
10	0.40363
11	0.37071
12	0.40430
13	0.40498
14	0.40363
Average	0.39522
Standard deviation	0.01626

Tab. 4. Measured value of ΔN at room temperature for ADXRS150 sensor

The latitude of measurements is $\varphi \approx 42.6°N$ (Sofia, Bulgaria) and $\psi_{Earth} \approx 3.0755 \cdot 10^{-3}$ °/s according to equation (9). Obviously the main factor in ΔN is $\Delta\psi_g$ for this sensor.

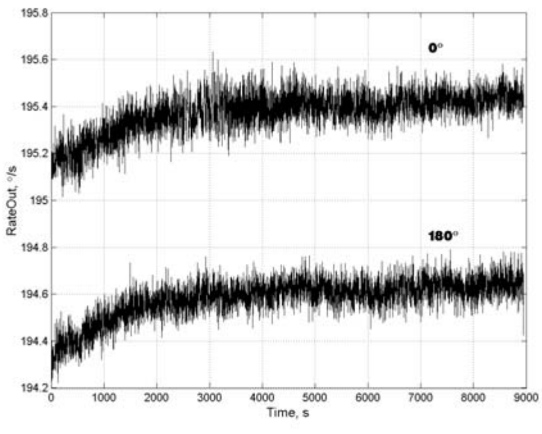

Fig. 3. Measured ADXRS150 output at positions 0° and 180°. The sensor is turned off prior to the beginning of the measurement.

Applying improved compensation to HZ1-90-100A sensor also gives good results in bias drift stability. This device has better parameters and performance than ADXRS150 and thus the drift values and the deviation from the average over time are smaller. Also, the sensitivity to linear acceleration is smaller for HZ1-90-100A reflecting to ΔN value.

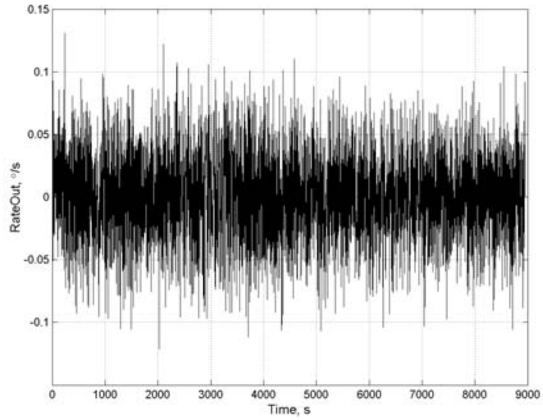

Fig. 4. Compensated output signal from Fig. 3. The average value is $5.595 \cdot 10^{-4}$ °/s with a standard deviation of $3.569 \cdot 10^{-2}$ °/s.

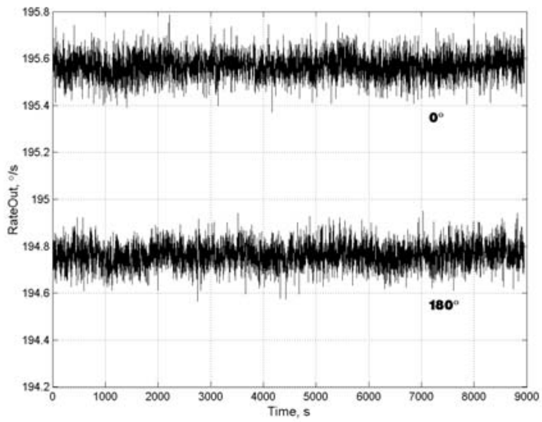

Fig. 5. Measured ADXRS150 output at positions 0° and 180°. The sensor is turned on prior to the beginning of the measurement.

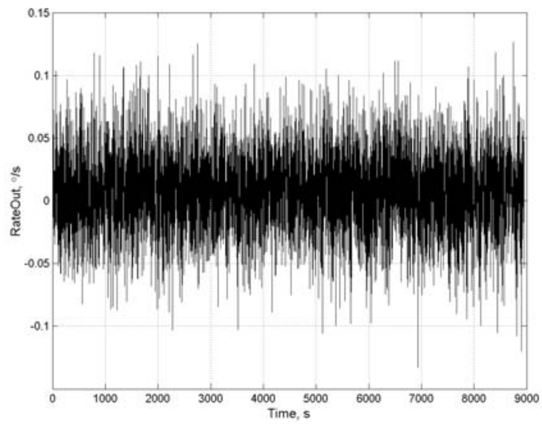

Fig. 6. Compensated output signal from Fig. 5. The average value is $7.535 \cdot 10^{-3}$ °/s with a standard deviation of $3.482 \cdot 10^{-2}$ °/s.

Based on the results from these two sensors, the conclusion can be made, that for devices with a stronger sensitivity to linear acceleration, the method's precision can be improved with the determination of ΔN.

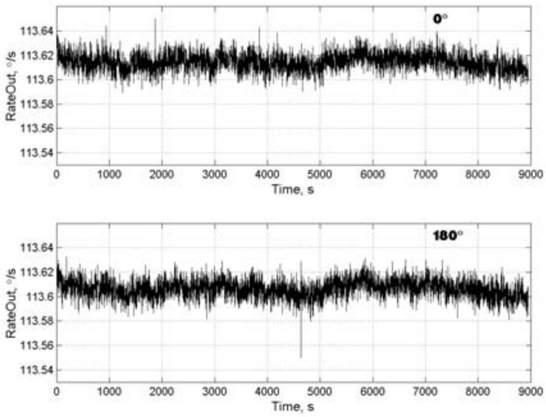

Fig. 7. Measured HZ1-90-100A output at positions 0° and 180°.

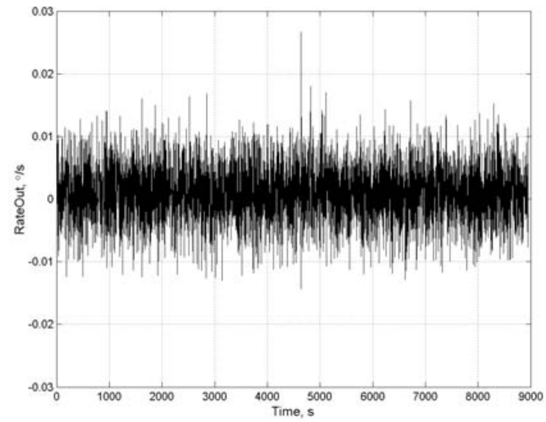

Fig. 8. Compensated output signal from Fig. 7. The average value is $-8.746 \cdot 10^{-4}$ °/s with a standard deviation of $4.588 \cdot 10^{-3}$ °/s.

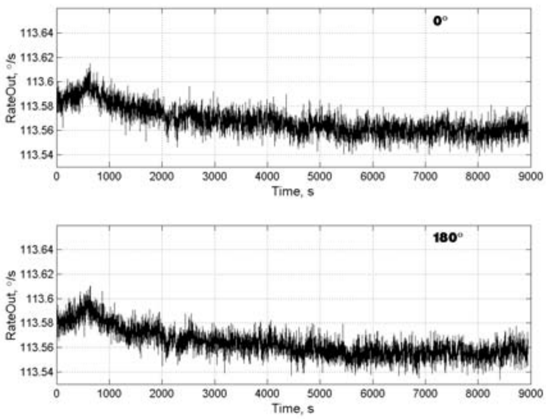

Fig. 9. Measured HZ1-90-100A output at positions 0° and 180°.

5. Conclusion

In this paper, an improvement of a known method for drift compensation in micromechanical gyroscopes is proposed. The improvement consists of accounting and removal of the linear acceleration sensitivity which may significantly degrade the precision of the method. A model of the sensor is devised, based on analysis of factors of influence when the sensor is used in different angular orientations.

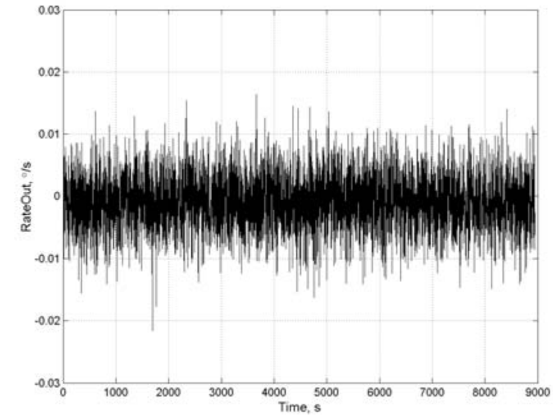

Fig. 10. Compensated output signal from Fig. 9. The average value is $1.004 \cdot 10^{-3}$ °/s with a standard deviation of $4.626 \cdot 10^{-3}$ °/s.

The result from applying the improved method with ΔN compensation shows a significant increase in long term stability of the bias.

With HZ1-90-100A a bias drift of 0.002°/s (for measurement time 2.5 h) is achieved. This value is one order lower than that specified by the manufacturer and in addition it is derived for a longer time interval and without any precautions for temperature stability.

ADXRS150 also shows a significant improvement in the drift, but with a higher noise. Higher sensitivity to linear acceleration strongly demands ΔN to be taken into account in order to improve the precision of the method.

Acknowledgements

The authors are grateful to “Sky Gate Ltd.” engineering department, which initiated and provided the experimental with materials and samples of sensors.

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About Authors...

Rumen ARNAUDOV was born in 1947 in Bulgaria and graduated from the Technical University in Sofia in 1972. In 1976 he joined the Faculty of Communications and Communication Technologies, Technical University of Sofia, where he received his PhD degree in Radio communication in 1982. Currently, he is Associated Professor of Measurements in communications and dean of Open Faculty. His research interests include measurements in communications, automated systems for information, processing and control.

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Prof. Ing. Jiří Pospíšil, DrSc. - In Memoriam 1939 – 2005

On April 4, 2005, the distinguished Czech scientist and university teacher Professor Dr. Jiří Pospíšil passed away at the age of uncompleted 66. From 1964 to 1970, his activities were associated with the Military Academy in Brno. In the years 1970 to 1972, he was with the Military Technical College in Cairo, Egypt. In 1974, he joined the Department of Radio Electronics, Brno University of Technology.

Prof. Pospíšil was the teacher and tutor of several hundreds of masters' and doctoral students. His educational and scientific activities were mainly focused on analog electronics, and circuit theory. In these areas, he educated young researchers, specialists, and followers.

Prof. Pospíšil has belonged to the well-known individualities in the Czech and Slovak academic and scientific community. He was engaged in state examination committees at the technical universities in Brno, Prague, and Bratislava. For several years, he served as the chair of the Electrical Engineering Society at the Brno University of Technology. He was the member of Scientific Board of his mother-like faculty, and of the Institute of Scientific Instruments in Brno (a part of the Czech Academy of Sciences).

Prof. Pospíšil belonged to the founders of the Radioengineering Journal, and for more than ten years, served as the Editor-in-Chief of this journal. He was also active as the chair of the technical program committee of the international conference Radioelektronika. Prof. Pospíšil was the Senior Member of the IEEE.

Personally, I have had the opportunity and honor to cooperate with Prof. Pospíšil at the Department of Radio Electronics, Brno University of Technology for several years. We never forget.

Professor Jiří Svačina
Head of the Dept. of Radio Electronics
Brno University of Technology